Physics-based Parameterizations of Air-sea Fluxes at High Winds Extension of CBLAST

Tetsu Hara
Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882
phone: (401) 874-6509   fax: (401) 874-6728   email: thara@uri.edu

Isaac Ginis
Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882
phone: (401) 874-6509   fax: (401) 874-6728   email: iginis@gso.uri.edu

Stephen E. Belcher
Department of Meteorology, University of Reading, Reading, RG6 6BB, UK
phone: (44) 118-931-6646   fax: (44) 118-931-8905   email: s.e.belcher@reading.ac.uk

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LONG-TERM GOALS

The long term goal of this project is to provide a new set of parameterizations of air-sea fluxes, which can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems. The new parameterizations will be constructed based on physical processes of the exchange of mass, momentum, heat, moisture, energy at the interface between the ocean and the atmosphere, and will be valid for the whole range of wind speeds.

OBJECTIVES

- We will extend the ongoing CBLAST studies by focusing on the following two areas:
- We will continue the basic study of the wave boundary layer. We will complete the inclusion of surface wave breaking effects on airflow. Specifically, two new physical processes will be included in the model:

  - momentum and energy flux into breaking waves due to the form drag of breaking crests

  - effect of spatial sheltering of shorter waves due to flow separation behind longer breaking waves.

- We will investigate how different surface wave fields affect air-sea momentum flux and scalar (heat, humidity) fluxes across the wave boundary layer.

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14. ABSTRACT
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- We will validate our coupled WBL/WW3 model by simulating the wave field under hurricanes observed during the CBLAST field programs and comparing the model results and available observational data. We will compare the directional surface wave spectrum from our model against direct SRA observations. We will compare the drag coefficient from our model against direct observations from aircraft.

APPROACH

The purpose of the new wave boundary layer (WBL) model is to predict the neutral drag coefficient for given 10-meter wind speed vector, surface wave spectrum, and breaking wave statistics. We have developed such a model without including the breaking wave effects (Hara and Belcher, 2004; Moon et al., 2004). Here, the model will be extended to include the effect of enhanced form drag by breaking waves as well as the effect of airflow separation due to breaking waves. If the breaking wave effects are set to be zero in the new model, it becomes identical to the existing nonbreaking model. The new wave boundary layer model will be constructed based on the following three components: (1) spatial sheltering due to air flow separation behind breaking wave crests, (2) conservation of momentum inside the wave boundary layer, (3) conservation of energy inside the wave boundary layer.

Coupling between the new WBL model and the WAVEWATCH III (WW3) model is made as described by Moon et al. (2004). Specifically, the spectrum near the peak is explicitly calculated using the WW3 model and the high frequency (tail) part is parameterized using the equilibrium wave spectrum model as described in 3.1. The resulting complete wave spectrum is then used to estimate the roughness length and the neutral drag coefficient.

We will investigate the wave spectrum and the roughness length (or neutral drag coefficient) under five Hurricanes - Fabian (2003), Isabel (2003), Frances (2004), Ivan (2004), and Jeanne (2004) - investigated during the CBLAST experiment and validate our model results against observations. In order to create more realistic wind forcing for the WBL/WW3 coupled model, we will also develop a new method of generating wind fields in hurricanes by blending the HRD winds and the message-based wind fields.

These tasks will be carried out by a graduate student under the supervision of the three PIs.

WORK COMPLETED

We have made progress in developing the new wave boundary layer model including the breaking wave effects. As a first step we examined a limiting condition where the wind input to breaking waves is much larger than the input to nonbreaking waves. A coupled model of breaking wave statistics, wind stress, and mean wind profile was developed under such conditions. A manuscript based on this model was published in Journal of Physical Oceanography (Kukulka et al., 2007).

We have extended the model to include both breaking and nonbreaking waves. A coupled model of wave spectra, breaking wave statistics, wind stress, and mean wind profile was developed. The model was applied for a wide rage of wind wave conditions from laboratories to the open ocean. Two mamuscripts based on this model will be submitted to Journal of Physical Oceanography (Kukulka and Hara, 2007a,b) shortly.

RESULTS

Coupled equations are derived governing the turbulent stress, wind speed, and the breaking wave distribution (total breaking crest length per unit surface area as a function of wave number), based on the assumption that in the equilibrium range of surface wave spectra the wind stress is dominated by the form drag of breaking waves. It is assumed that smaller scale breaking waves are sheltered from wind forcing if they are in airflow separation regions of longer breaking waves (spatial sheltering effect). Without this spatial sheltering, exact analytic solutions are obtained; with spatial sheltering asymptotic solutions for small and large scale breakers are derived. In both cases, the breaking wave distribution approaches a constant value for large wave numbers (small-scale breakers). For low wave numbers, the breaking distribution strongly increases with wind forcing. If the equilibrium range model is extended to the spectral peak, the model yields the normalized roughness length (Charnock coefficient) of growing seas, which increases with wave age and is roughly consistent with earlier laboratory observations (Figure 1). Model results suggest that the wind stress over fully developed seas is not dominated by the form drag of breaking waves. For a given wind stress the breaking distribution near the spectral peak rapidly decreases as the wave field develops (Figure 2).

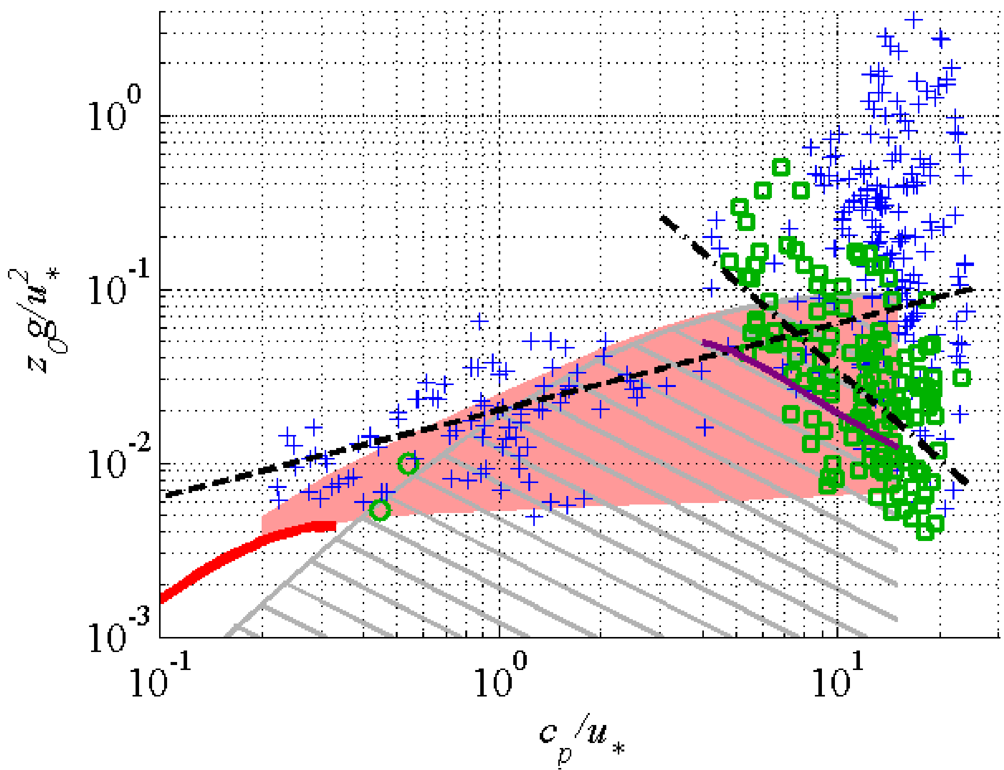

Figure 1: Nondimensional roughness length (Charnock coefficient) is plotted versus wave age. Pink area is the range of results with both breaking and nonbreaking waves (Kukulka and Hara 2007b). Purple line is the result with threshold saturation spectrum decreasing with wave age. Red line is the result with breaking waves only (Kukulka et al. 2007). Grey hatched area is the range of results with nonbreaking waves only. Dashed line and dash dot line are empirical estimates by Toba et al. (1990) and Drennan et al. (2003), respectively. Blue crosses are data compiled by Toba and Ebuchi (1991). Green squares are field data from Drennan et al. (2003).Green circles are laboratory data from Donelan et al. (2004).

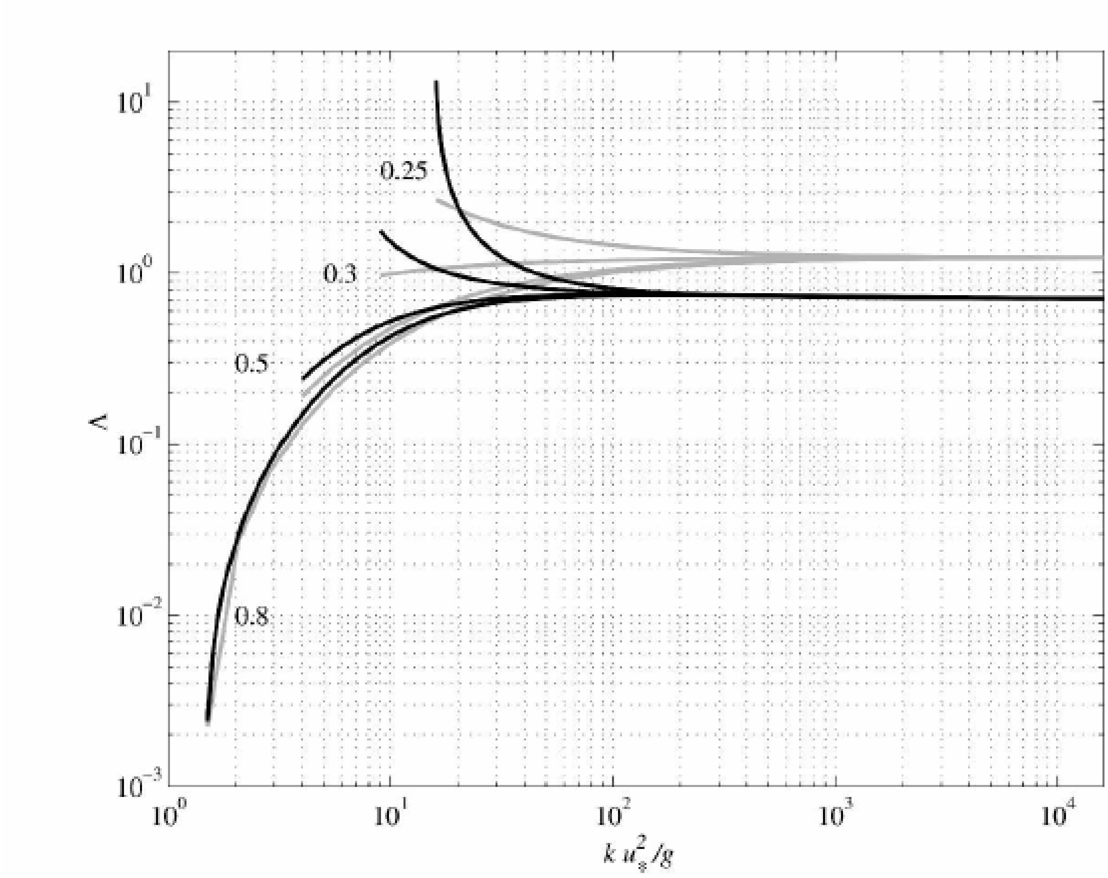

Figure 2. Breaking wave distribution for different wave ages (indicated by numbers in the figure) is shown against normalized wavenumber. The left edge of the line corresponds to the spectral peak. Black and grey line shows results without and with spatial sheltering. As the wave field develops the number of breakers near the peak rapidly decreases.

We have developed a new coupled wind and wave model that includes the enhanced form drag of breaking waves. Breaking and non-breaking waves induce air-side fluxes of momentum and energy in a thin layer above the air-sea interface within the constant flux layer (the wave boundary layer). By imposing momentum and energy conservation in the wave boundary layer and wave energy conservation, we have derived coupled nonlinear advance-delay differential equations governing the wind speed, turbulent wind stress, wave height spectrum, and the length distribution of breaking wave crests. The system of equations is closed by introducing a relation between wave dissipation (due to breaking waves) and the wave height spectrum. Wave dissipation is proportional to nonlinear wave interactions, if the wave curvature spectrum is below the threshold saturation level. Above this threshold, however, wave dissipation rapidly increases, so that the wave height spectrum is limited.

First, numerical solutions have been obtained for mature wind-driven seas for which the dominant wind forcing occurs at higher wave numbers away from the spectral peak. Modeled wave height curvature spectra as functions of wave number are consistent with observations. Breaking waves affect only weakly the wave height spectrum. Furthermore, the wind input to waves is dominated by non-breaking waves close to the spectral peak. Shorter breaking waves away from the spectral peak, however, can support a significant fraction, which increases with wind speed, of the total air-sea momentum flux.

Next, numeric solutions for a wide range of model parameters have been obtained, including conditions of young, strongly forced wind waves. Furthermore, the spatial sheltering effect has been introduced, so that smaller waves in air flow separation regions of breaking longer waves cannot be forced by the wind. For many parameter combinations, the input to waves close to or far away from the spectral peak is either dominated by breaking or non-breaking waves. In this case simple analytic solutions are found. Model results depend critically on the threshold of the wave height saturation spectrum that limits wave amplitudes (the threshold saturation level). The smaller this threshold (waves are more prone to breaking), the greater is the influence of breaking waves on momentum and energy uptake from the wind. If breaking waves dominate the wind input, previous solutions of a breaking only model are recovered. In this case, the one dimensional breaking wave distribution as function of wavenumber converges to a constant. If, on the other hand, non-breaking waves dominate the wind input, the breaking wave distribution is more complex.

Our model results of the Charnock coefficient are consistent with ealier field and laboratory observations (Figure 1). For very young seas the full model result converges to the result of the breaking wave only model, and the Charnock coefficient increases with wave age. For more developed seas in the field, the observed decrease in normalized roughness length with wave age for moderate wind conditions may be due to a decrease of the threshold saturation level with wave age (Figure 1). The low drag coefficient observed for high wind conditions may be explained by assuming a relatively low threshold saturation level, i.e. a dampened wave height spectrum.

IMPACT/APPLICATIONS

This program of work promises a one dimensional (1d) model of the atmospheric and oceanic boundary layers in the vicinity of the air-sea interface that accounts for both breaking and non-breaking waves. The model will, given the ten meter wind speed, temperature and humidity and surface wave parameters, produce wave breaking statistics, wind and current profiles, fluxes and flux profiles and the turbulent kinetic energy budgets through the 1d air and water wave boundary layers. These results may be used as a basis for any future modeling efforts of ocean-atmosphere interaction processes.

RELATED PROJECTS

TH has a NSF(OCE) project (2005-2008) to validate and improve the new wave boundary layer model including breaking wave effects against laboratory observations performed at University of Miami.

New knowledge gained from our study is being incorporated in coupled atmosphere-wave-ocean numerical models under a NSF(ATM) project (2004-2008) by IG and TH. Current numerical wave models are not capable of predicting accurately short wind waves at frequencies much higher than the spectral peak. Instead they patch a parameterized form of spectra. More accurate information about short wind wave spectra and their breaking statistics resulting from this study will improve the accuracy of the numerical wave prediction and will thus enhance the performance of coupled numerical models.

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PUBLICATIONS

Kukulka, T., T. Hara, and S. E. Belcher, 2007. A model of the air-sea momentum flux and breaking wave distribution for young, strongly forced wind-waves, J. Phys. Oceanogr., 37, 1811–1828 [published, refereed].